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A HIERARCHICAL FRAMEWORK FOR COUPLING SURFACE FLUXES TO ATMOSPHERIC GENERAL CIRCULATION MODELS: THE HOMOGENEITY TEST

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1. INTRODUCTION

The atmosphere and the biosphere are inherently coupled to one another. Atmospheric surface state variables such as temperature, winds, water vapor, precipitation, and radiation control biophysical, biogeochemical, and ecological processes at the surface and subsurface. At the same time, surface fluxes of momentum, moisture, heat, and trace gases act as time-dependent boundary conditions providing feedback on atmospheric processes. To understand such phenomena, a coupled set of interactive models is required.

Costs are still prohibitive for computing surface/subsurface fluxes directly for medium-resolution atmospheric general circulation models (AGCMs), but a technique has been developed for testing large-scale homogeneity and accessing surface parameterizations and models to reduce this computational cost and maintain accuracy. This modeling system potentially bridges the observed spatial (10^0 to 10^{10} m^2) and temporal ranges (10^0 to 10^8 s), yet allows the incorporation of necessary details about individual ecological community types or biomes and simulates the net momentum, heat, moisture, and trace gas fluxes. This suite of coupled models is defined here as the hierarchical systems flux scheme (HSFS). Section 2 discusses the HSFS procedure, Section 3 describes the completed and tested homogeneity test (HTEST), and Section 4 discusses the results and implications of HTEST.

2. HIERARCHICAL SYSTEMS FLUX SCHEME

An HSFS has been proposed by Miller and Foster (1992) as a means to

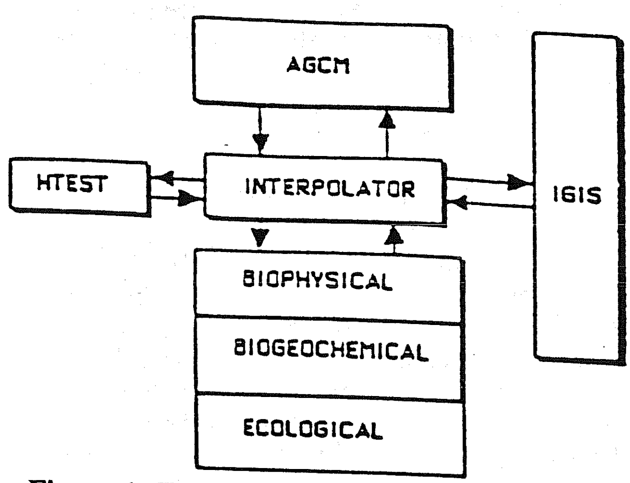

Figure 1. The HSHS, consisting of five components: (1) an AGCM, (2) the HTEST, (3) the interpolator, (4) the IGIS, and (5) surface models.

couple subgrid processes at the surface and subsurface to AGCM atmospheric physics in a modular system to be run on high-performance computers. The HSFS consists of the five major components illustrated in Figure 1: (1) an AGCM, which provides a medium-resolution simulation of the atmospheric circulation; (2) the HTEST, a procedure for identifying regions of defined homogeneity of surface type within AGCM grid cells; (3) a set of surface/subsurface biophysical, biogeochemical, and ecological parameterizations and models to be run within homogeneous regions for specific biomes; (4) an interpolator that transfers information between the medium-resolution AGCM and fine-resolution surface/subsurface process models; and (5) an interactive geographic information system (IGIS), which passes land characteristic information to HTEST.

The HSFS will simulate a multidirectional flow of information between the system components. Surface state variables updated by the AGCM control the process models, while net surface fluxes are read into the AGCM as time-dependent surface boundary conditions. Ideally, vegetation changes, succession, and various other surface type changes will be incorporated as part of IGIS and HTEST. The modular design of the HSFS will serve as a "plug-compatible" platform for the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS,1992) which will provide various surface models. HTEST, together with the interpolator, acts as the interface for the process models and the general circulation model, with the IGIS storing the updated surface history.

3. HTEST PROCEDURE

The hierarchical systems flux model uses a procedure called HTEST to identify subregions of defined homogeneity within an AGCM grid cell. The procedure is to be applied at the beginning of a simulation and repeated at predetermined intervals if succession occurs. Homogeneity is defined in terms of percentage uniformity in vegetational, soil, and topographic characteristic types. The degree of uniformity required within a subregion will depend on accuracy requirements, available computational resources, and the observed variability in flux rates between different surface types.

HTEST identifies homogeneous regions within an AGCM grid cell by applying a homogeneity test to the entire cell in the following steps: (1) determination of the area represented by AGCM grid point location, (2) mapping of subgrid IGIS data onto the region, and (3) computing the percent area of each characteristic type over the AGCM grid point area. If the area is uniform (e.g., if a dominant surface type occurs at a critical value such as 95%) then the region is considered homogeneous. If the AGCM grid point area is not uniform (if a dominant surface type represents less than a critical value) then the region is heterogeneous and the test fails. If the test fails, the cell is divided in two, and the test is repeated in each subcell until the homogeneity criterion is met or a defined minimum resolution has been reached. The bisections alternate N-S and W-E with each division.

Application of the HTEST procedure is intended to generate a sparsely defined or telescoping grid in which fewer than 10% of the AGCM cells are partitioned. As selective telescoping occurs in regions where horizontal gradients of flux are high, this approach should permit a significant improvement in the accuracy of simulation of surface fluxes, without greatly increasing computational costs.

In general, the number of bisections is limited by the resolution of the IGIS data. For example, a 0.25° by 0.25° surface resolution will allow seven bisections on a global 3° by 3° resolution. However, the Defense Mapping Agency has available surface data at 1 km by 1 km resolution and specific regions with a high degree of heterogeneity may be identified with resolution well below 0.1° by 0.1°. The availability and use of such sparse data sets has been suggested by R. Harris (personal communication, 1991).

4. DISCUSSION OF HTEST PROCEDURE

The completed HTEST module can evaluate all AGCM grid cells for homogeneity, bisect any heterogeneous rectangular cell clusters down to a minimum resolution, and provide uncertainty information. Application of the HTEST procedure is intended to generate a sparsely defined telescoping grid in which fewer than 20% of the AGCM cells are partitioned. As selective telescoping occurs in regions of high surface gradients, the accuracy of simulation should be greatly enhanced. Furthermore, coupling the atmospheric model to ecosystem models will require the ability to scale homogeneous types down to the landscape level with minimal aggregation. This telescoping approach will ultimately allow such calculations.

HTEST is illustrated here for several case studies, to highlight the computational savings with increased accuracy. Figure 2 shows an 8° x 10° AGCM grid for a region in the northern Great Plains of the United States. The coarse scale chosen here is for illustrative purposes and is not necessarily the intended scale for actual use in HSFS, as

HTEST can scale to any grid system. This area is centered about 105°W longitude and 45° N latitude. The upper left corner of Figure 2 corresponds to the geographic southwest, and the lower right corner corresponds to the northeast. Currently a 1°x 1° vegetation resolution (Matthews, 1983) is used, but a 0.1° x 0.1° resolution will be implemented in the near future.

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Figure 2. AGCM grid cell of size 8° x 10°. Vegetation types are noted as in the text.

The 8° x 10° area consists of 80 vegetation cells, with 34 adjacent vegetation cells of type 28 (meadow, short grassland, no woody cover), 26 adjacent cells and 1 isolated cell of type 27 (medium grassland, no woody cover), and 11 adjacent cells and 1 isolated cell of type 25 (tall/medium/short grassland with shrub cover). There are also 4 vegetation cells of type 14 (evergreen needle-leaved woodland), 2 adjacent to one another and 2 isolated. Vegetation types 18 (evergreen needleleaved), 21 (xeromorphic shrubland/dwarf shrubland), and 23 (tall/medium/short grassland with 10-40% woody tree cover) occur once in single cells.

The HTEST reduces the 80-cell description by bisecting a minimum number of times until a set of adjacent vegetation cells is represented as a newly defined subcell with dimensions based on the number of bisections. Homogeneity is defined as a fractional area of a single vegetation type that is greater than or equal to H, the HTEST critical value. In the set of homogeneous subcells produced, each subcell retains the percent minimum homogeneity.

Figure 3 depicts the results of HTEST when the critical homogeneity H is set to (a) 0.0, (b) 0.4, (c) 0.5, (d) 0.6, (e) 0.7, (f) 0.8, (g) 0.9, (h) 0.95, and (i) 1.0. The first two cases (H = 0.0, 0.4) compute a single dominant surface type over an AGCM grid cell. Coupling any atmosphere-biosphere model directly to an AGCM will allow computations either at this resolution or for integrated cell averages. At H = 0.5 (Figure 3c), the AGCM cell is computed as 2 vegetation types, 28 and 27, divided along a north-south line in the middle of the cell. Figure 3d indicates that at H = 0.6 the single AGCM cell has eight subgrids. The three dominant vegetation types, 27, 28, and 25, are seen as well as type 14. Type 14 occurs only once and is seen because it happens to be in a subcell that was 50% type 14 and 50% type 25; thus, a further division was required for H = 0.6 for the entire AGCM grid subcell. At H = 0.7 (Figure 3e) a second subcell is of type 14, and at 0.8 (Figure 3f) 3 subcells are of type 14. The other vegetation types are also more clearly defined as the H value increases. At H = 0.8, the vegetative type 25 in the southeast corner is now present. At H = 0.9 (Figure 3g), type 18 is seen at the southwest corner. At HTEST values at 0.95 and higher (Figures 3h and 3i), the original vegetation is completely mapped at the resolution of the vegetation data.

Figure 4 shows the number of vegetation cells as a function of the homogeneity level. For this specific case, below a minimum homogeneity of 50%, only one processor will be called to run surface/subsurface models for a vegetation type of to 28. Between H = 0.60 and H = 0.90, the increase in the number of required processors is nearly linear. The maximum number of processors required, reached at H = 0.95, is 40, representing a relative computational savings of 50% in comparison with running each vegetation cell separately. A further possible reduction, yet to be implemented, would involve new subcell categories devised by merging computed adjacent subcells of the same characteristic type.

Two other locations were analyzed for minimum homogeneity and processor requirements. These are the Brazilian rain forest at 60° W longitude and 10° S latitude and the coastal Alaskan/British Columbian lowlands at 130°W longitude and 55° N latitude. Figure 4 compares the number of subplots as a function of H for each of these three cases. In each case there is an H value below which only one processor is required to compute surface fluxes, a region of nearly linear increase, and a maximum H value where 100% of the original plot is preserved. Below H = 0.70, only one processor is required for the rain because of the smooth vegetation gradient as defined by Matthews (1983). In the coastal lowland, 100% of the original plot is preserved at H = 0.80. These differences reflect the variations in surface type within each AGCM cell, not the differences among AGCM cells. A fourth case in Figure 4 represents oceanic regions far from land surfaces. For oceans, a single processor will adequately represent several AGCM cells. In all cases, the value H = 1.00 requires sufficiently few processors to be used as the criterion for future studies.

5. CONCLUSIONS

The HTEST provides a means for interfacing surface/subsurface fluxes at various scales to an AGCM. The utility of this scaling tool will prove useful in climatic feedback studies that focus on atmospheric, biophysical, biogeochemical, and ecological processes with increased accuracy. HTEST reduces the computational time with increased accuracy in a direct method for computing subgrid surface areas. Efficient partitioning of heterogeneous areas is a necessary component to scaling fluxes and state fields.

Ideally, simulations of climate change and successions over 100 to 1,000 years can be implemented by using HTEST in conjunction with the HSFS framework. Although computational costs will still be quite high if process models are run for each subgrid, the approach described above will drastically reduce these costs. When this system becomes operational, detailed questions related to the feedbacks between the biosphere and the atmosphere can be fully investigated.

References:

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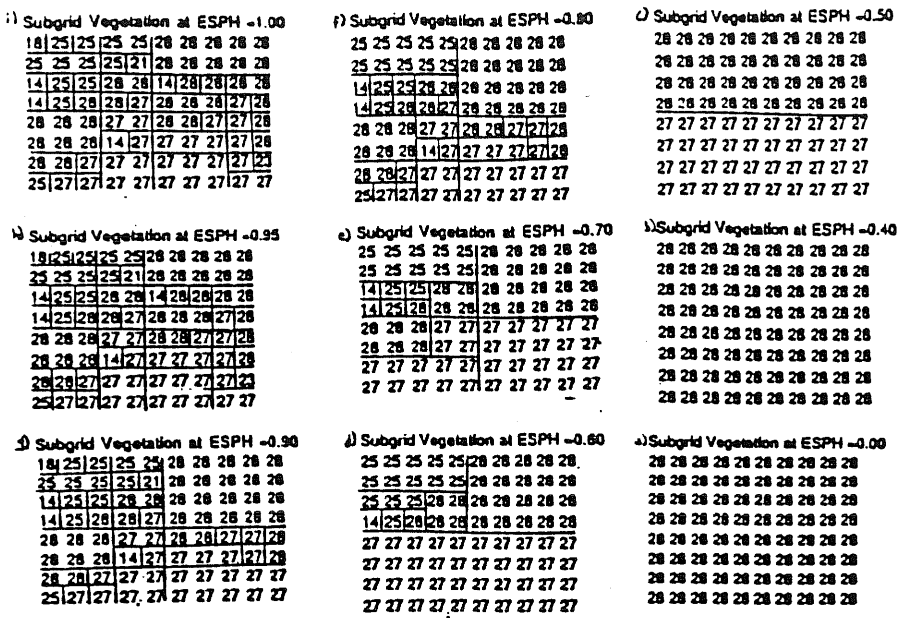

Figure 3. Resultant HTEST for H = (a) 0.0, (b) 0.4, (c) 0.5, (d) 0.6, (e) 0.7, (f) 0.8, (g) 0.9, (h) 0.95, and (i) 1.00.

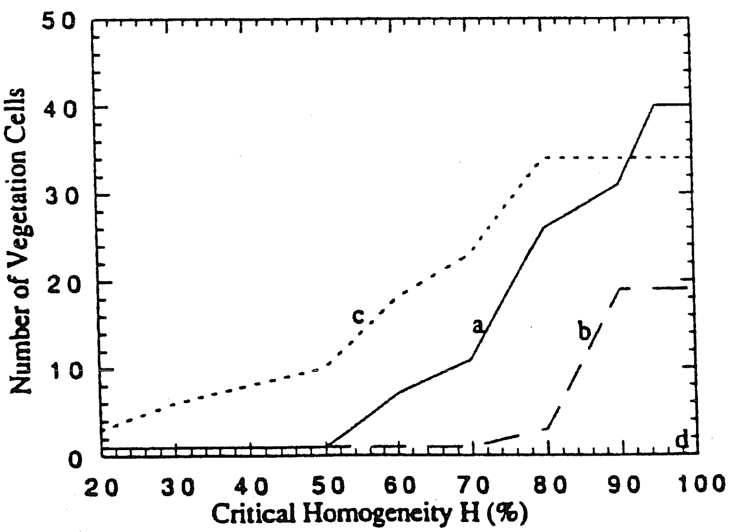

Figure 4. Plot of number of processors verses minimum homogeneity for (a) mid-latitude grasslands (105W and 45 N), (b) Brazilian rain forest (130 W and 55 N), (c) coastal boreal lowlands (130 W annd 55 N), and (d) oceans.